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NAMRL-09-32

# VECTION AND MOTION THRESHOLDS AS A FUNCTION OF CONTRAST

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# Report Documentation Page

| Report Documentation Page | Form Approved<br>OMB No. 0704-0188 |
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| 1. REPORT DATE<br>**25 AUG 2009** | 2. REPORT TYPE | 3. DATES COVERED |
|---|---|---|

| | |
|---|---|
| 4. TITLE AND SUBTITLE<br>**Vection and Motion Thresholds as a Function of Contrast** | 5a. CONTRACT NUMBER<br>5b. GRANT NUMBER<br>5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S)<br>**Frederick Patterson; Yancy York** | 5d. PROJECT NUMBER<br>5e. TASK NUMBER<br>5f. WORK UNIT NUMBER<br>**70802** |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**Naval Aerospace Medical Research Laboratory,280 Fred Bauer Street,Pensacola,FL,32508** | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSOR/MONITOR'S ACRONYM(S)<br>11. SPONSOR/MONITOR'S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release; distribution unlimited.**

13. SUPPLEMENTARY NOTES

14. ABSTRACT
**Background/Introduction. Vection can be defined as a sensory-spatial illusion t hat creates false sensations of self motion, in either linear or angular directi ons. Although false perceptions of self motion are common, visual characteristi cs linked to this type of illusion are not fully understood. Vection can be strongly influenced by various physical aspects, such as optical velocity of the visual stimulus, spatial frequency, and field of view. Although previous research documents how perceived motion can be influenced by several variables associated with visual contrast, they do not provide insight into the relationship between color variation and onset of vection illusion. Since very little is known about the relationship between visual contrast thresholds and susceptibility to vection, and even less is known about the impact of color variations on self motion illusions; it was deemed beneficial to further evaluate this topic from a qualitative perspective. Method. This study was conducted on 20 aviator candidates awaiting flight training. A Visual Vestibular Sphere Device (VVSD) was used to elicit the illusion of self-motion (vection) while subjects viewed the moving VVSD surround through a window that allowed visual contrast to be varied; this method led to the determination of contrast thresholds for the detection of surround motion and the onset of vection. The objective was to determine the effect of color saturation altered visual contrast on detection of surround motion and vection. Results. The threshold for detection of vection was 2.5% contrast. A similar contrast threshold was obtained for detection of surround motion; however, surround motion was reported sooner than vection at a given contrast. Above threshold, lower contrast stimuli were associated with longer latencies to onset of vection and lower ratings of vection strength (realism of the illusion) at the time of onset of vection. Conclusions. Vection was triggered readily at very low levels of visual contrast. It appeared that as long as the observers could detect any surround motion, they reported vection. Nevertheless, the vection illusion was stronger and was elicited faster under conditions of high contrast.**

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT<br>**unclassified** | b. ABSTRACT<br>**unclassified** | c. THIS PAGE<br>**unclassified** | | **28** | |

## Summary

*Background/Introduction.* Vection can be defined as a sensory-spatial illusion that creates false sensations of self motion, in either linear or angular directions. Although false perceptions of self motion are common, visual characteristics linked to this type of illusion are not fully understood. Vection can be strongly influenced by various physical aspects, such as optical velocity of the visual stimulus, spatial frequency, and field of view. Although previous research documents how perceived motion can be influenced by several variables associated with visual contrast, they do not provide insight into the relationship between color variation and onset of vection illusion. Since very little is known about the relationship between visual contrast thresholds and susceptibility to vection, and even less is known about the impact of color variations on self motion illusions; it was deemed beneficial to further evaluate this topic from a qualitative perspective.

*Method*. This study was conducted on 20 aviator candidates awaiting flight training. A Visual Vestibular Sphere Device (VVSD) was used to elicit the illusion of self-motion (vection) while subjects viewed the moving VVSD surround through a window that allowed visual contrast to be varied; this method led to the determination of contrast thresholds for the detection of surround motion and the onset of vection.

*Objective*. Determine the effect of color saturation altered visual contrast on detection of surround motion and vection.

*Findings.* The threshold for detection of vection was 2.5% contrast. A similar contrast threshold was obtained for detection of surround motion; however, surround motion was reported sooner than vection at a given contrast. Above threshold, lower contrast stimuli were associated with longer latencies to onset of vection and lower ratings of vection strength (realism of the illusion) at the time of onset of vection.

*Discussion*. Vection was triggered readily at very low levels of visual contrast. It appeared that as long as the observers could detect any surround motion, they reported vection. Nevertheless, the vection illusion was stronger and was elicited faster under conditions of high contrast.

## Introduction

Vection can be defined as a sensory-spatial illusion that creates false sensations of self motion, in either linear or angular directions. One of the most recognized forms of this misperception occurs when a driver is seated in a stationary car, focused on something inside the automobile. If, in this situation an adjacent car unexpectedly backs up, the optical flow generated in the (stationary) driver's peripheral vision will often trigger a false sensation (vection illusion) that the parked car is moving forward.

Vection illusions can also occur when helicopter pilots enter a low hover over loose surface material such as sand, snow, or water (figure 1; U.S. Naval Flight Surgeon's Manual, 1991). *"Typically, helicopter vertical vection illusions involve low hover situations where particles of loose surface material are blown up from the ground and then forced down over the windscreen by the rotor wash. As the particulate matter begins to block visibility of critical ground references, the pilot's outside view will be replaced by rotor wash dust particles or water droplets flowing downward over the windscreen. These particles will tend to generate downward optical flow images on the pilot's central and peripheral retina, thereby creating the risk of experiencing a vection illusion that will provide false sensations of increasing altitude. The danger associated with this form of vection induced disorientation is: if a pilot lowers the collective in response to a false perception of exaggerated lift, it will lead to an unintended descent and thereby increase risk of catastrophic ground impact (Patterson, 2008)."*

When a pilot's view is degraded by clouds of dust kicked up by a helicopter's rotor downwash, the term "brownout" is often associated with the resultant loss of outside spatial references and vection induced disorientation. The extreme danger associated with this condition is reinforced by the following Department of Defense statement: *"Helicopter brownouts are probably the most significant of all military operational concerns when landings are required in the desert environment. Brownout-related mishaps account for a significant number of incidents resulting in severe injury, loss of life and aircraft. Across the Department of Defense, more helicopters are lost to DVE [degraded visual environments] than to enemy fire. Three out of four helicopter accidents in Iraq and Afghanistan have been attributed to Brownout. DoD accidents attributed to DVE cost approximately $100 Million per year." (DARPA, 2006).*

*Figure 1*: The picture on the left illustrates how rotor wash can blow sand upward and then force it down through the rotors over the windscreen, thereby creating a "brownout" that blocks the pilots outside view. The picture on right provides an example of how a similar situation happens when hovering over water.

Although false perceptions of self motion are common, visual characteristics linked to this type of illusion are not fully understood. A review of the literature indicates vection can be strongly influenced by various physical aspects, such as optical velocity of the visual stimulus, spatial frequency, and field of view. Examples of previous research demonstrate that perceived velocity of self-rotation in circular vection is directly proportional to the optical velocity of a visual stimulus, up to 90 deg/sec (Howard, 1986; Brandt, Dichgans, & Koenig, 1973). Similarly, spatial frequency, which can be described as spacing of detail within a visual stimulus (figure 2), has been shown to increase perception of illusory self-motion as spatial separation of visual targets becomes greater (Diener, Wist, Dichgans, & Brandt, 1976). With regard to variation within fields of view, Stanny (2002) reported: if all other variables are held constant, wide (as opposed to narrow) fields of view are the most effective for eliciting vection.

Reducing luminance or brightness from high to extremely low levels has been reported as having no effect on vection, which suggests that onset of vection may be characterized as an "all" or "none" response. Additionally, vection has been shown to occur even with significant blurring of the visual stimulus, similar to what might occur during brownout conditions (Leibowitz, Podemer, & Dichgans, 1979). A related question, which has yet to be explored thoroughly is how predominant are vection illusions during daylight conditions with low visual contrast. It is possible that vection may occur readily in well illuminated environments with low contrast, just as it does under fairly dark or blurry conditions. Answering this question could be important for further identification of flight safety requirements during flight operations that involve degraded visual conditions.

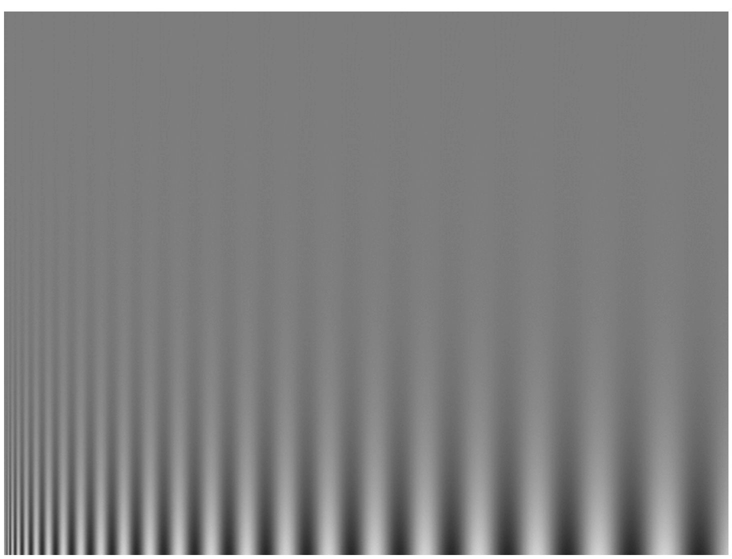

*Figure 2:* This image illustrates visual contrast variables such as spatial frequency and color (gray) saturation. The vertical coordinates color contrast and the horizontal axis indicates specific variations in spatial frequency contrast.

Although the cited studies document how perceived motion can be influenced by several variables associated with visual contrast, they do not provide insight into the relationship between color variation and onset of vection illusion. To complicate things further, the term visual contrast has become somewhat controversial with regard to its definition; the visual scientist Dr. Travnikova (1985) accurately summarized this problem with his statement that, *"There are many possible definitions of contrast. Some include color; others do not. Such a multiplicity of notions of contrast is extremely inconvenient. It complicates the solution of many applied problems and makes it difficult to compare the results published by different authors."* In very general terms, visual contrast can be described as the difference in visual properties that make an object (or its representation in an image) distinguishable from other objects and the background. Among the researchers working in this area there does appears to be a consensus that visual contrast is made up of at least four subcomponents identified as brightness (luminance or illumination), shape, size, and color. Although vection threshold values for brightness, size, and shape (blurriness) have been proposed by Leibowitz, et. al. (1979); threshold values related to onset of vection and color have not been established.

To illustrate how color contributes toward defining visual contrast, an understanding of several technical terms is required. Visual scientists agree that color has three principal properties referred to as hue, saturation, and value (HSV) (Smith, 1978). The following definitions, which describe these variables, are frequently used by display engineers as standardized terms that help establish design specifications for color generating devices.

> Hue refers to the dominant light spectrum contained within primary and secondary colors (i.e., variations of red, blue, yellow, orange, violet, and green (figure 3).
>
> Saturation refers to the dominance of a particular hue within a color. By selecting different points on a color wheel radius (figure 3), different spectrums of light (hues) can be combined (saturated) with one another.
>
> Value of a color is defined as the lightness or darkness of a color. In terms of a spectral definition of color, value describes the overall intensity or strength of the light. If hue can be thought of as a dimension going around a wheel, then value is like an axis running through the middle of the wheel (Figure 3).

Since very little is known about the relationship between visual contrast thresholds and susceptibility to vection, and even less is known about the impact of color variations on self motion illusions; it would be beneficial to further evaluate this topic from a qualitative perspective.

Limited inferences about vection can be drawn from a study that evaluated illusory (induced) motion during exposure to a vertically striped visual surround (Mapperson & Lovegrove, 1989). The results of this research revealed that increasing visual contrast components of shape and size, increase the illusion of induced motion when viewing a

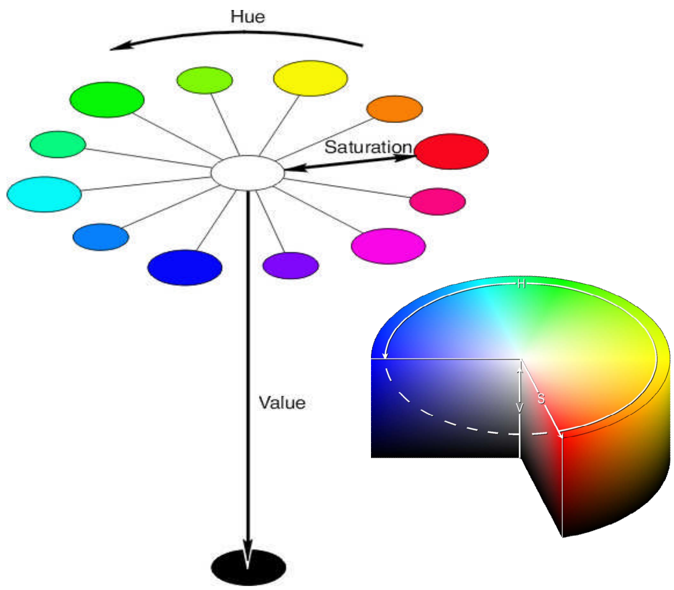


*Figure 3:* Two versions of the HSV color wheel demonstrating the relationships of hue, saturation and value.

central target. A second study conducted by Sauvan and Bonnet (1993) explored these same visual contrast variables, and found that perceived velocity of illusory self-motion (circular vection) increased proportionally with speed of the surround stimulus and spatial frequency (size and spacing) of the visual targets. Although very little has been done to investigate color variations and vection, one recent experiment indirectly evaluated these variables while investigating the impact that perceived motion has upon motion sickness. The results of this study indicated that, "chromaticity [color] may affect how much an observer's visual environment appears to be stationary, perhaps because chromaticity is such a common feature of the stationary environment in which our visual system evolved" (Bonato, Bubka, & Alfieri, 2004).

Although several studies have successfully identified some of the relationships between perception of self motion and components of visual contrast, there is very little information available as to how different aspects of color impact visually induced vection illusions. The current study represents an attempt to expand our knowledge of this problem by determining what is the minimum color saturation value necessary for inducing self motion illusions. The hypothesis of this experiment was aimed at determining whether variations in color saturation have an impact upon visual contrast and thereby alter the strength and latency of circular motion (vection) illusion.
The specific goals of this research were to:

- Determine the minimum level of visual contrast color saturation necessary for triggering vection illusion during exposure to a circular motion visual stimulus.

- Determine how long it takes for circular vection illusion to occur, after a visual stimulus is introduced.

By identifying these vection thresholds, cockpit designers will be able to improve accuracy of cockpit and simulator design specifications, and aircraft accident investigators may gain further insight into the causes of brownout spatial disorientation.

## Method

*Overview of Experimental Plan*: The design for this study contained a single independent variable that was created by manipulating the color saturation of visual targets painted on a spherical surround (figure 4). In addition to this single independent measure, the following four dependent variables were evaluated:

- Sensation of sphere motion with no vection illusion.
- Sensation of vection illusion.
- Subjective assessment of vection strength.
- Latency between detection of sphere motion and onset of vection.

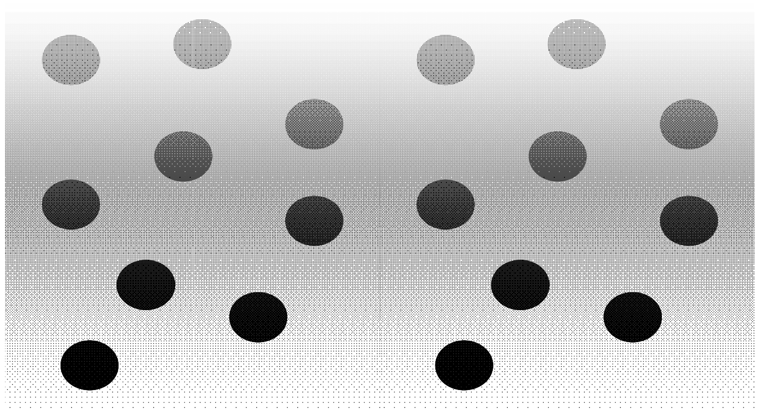

*Figure 4:* Example of visual target dot pattern painted on the interior surface of the visual surround dome.

For the purpose of this study the independent variable of color saturation was created by introducing increasing levels of gray as a visual overlay on a moving black and white dot pattern (visual stimulus); the variations in gray saturation ranged from zero (no gray saturation) to %100 percent (total visual block of white and black dot pattern).

*Subjects*: To test the hypothesis of this study, twenty healthy, active duty military volunteers were recruited from aviation candidates awaiting primary flight training at Naval Air Station, Pensacola**.** Past susceptibility to motion sickness was rated to exclude susceptible participants; volunteers who scored higher than the 50th percentile on the Motion Sickness Symptom Questionnaire (Golding, 2006) were excluded, since a subject

with a high score would have an increased probability of becoming too ill to complete the repetitive sessions required for establishment of the vection threshold values.

This study was approved by the Naval Aerospace Medical Research Laboratory Institutional Review Board in compliance with all applicable Federal regulations governing the protection of human subjects. A written informed consent was obtained and a copy was provided to each participant (appendix A). Participation was strictly voluntary with no compensation provided to the subjects.

*Apparatus:* The design of this study required presentation of a moving visual stimulus (vection inducing) that could be altered with respect to color saturation of the visual target pattern. To generate a moving visual surround, experimenters utilized the visual vestibular sphere device (VVSD) located at NAMRL, NAS Pensacola, Florida. The VVSD is a 12-foot diameter spherical surround that provides subjects with a place to sit in the lower center portion of the VVSD dome (Figure 5). The interior of the VVSD has a white surface with 10% coverage of randomly-placed black dots, with each dot subtending approximately 4.7° of visual angle at the eye of the volunteer. For this study, the subjects were held stationary while they remained seated upright in the center of the sphere. With subjects in place, the sphere was slowly rotated at 15 deg/sec (2.5 rpm) in an earth-vertical yaw direction. The chosen visual stimulus velocity was selected because in the past, this procedure was shown to elicit strong vection illusions without inducing symptoms of motion sickness over relatively short periods of time (Lawson, 2006).

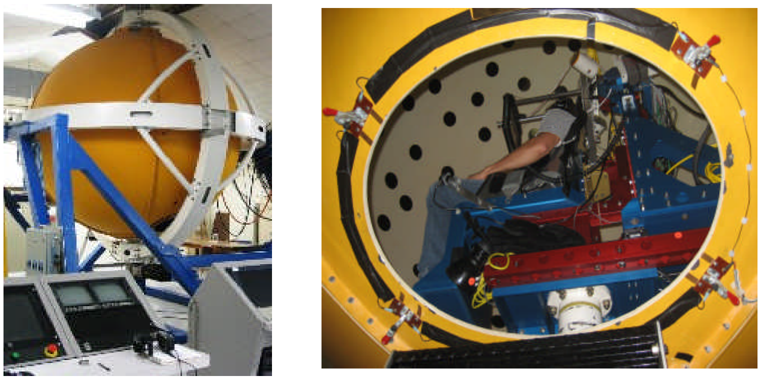

*Figure 5:* The visual vestibular sphere device (VVSD), outside and inside views.

Manipulating color saturation of the independent measure (rotating dot pattern) was accomplished by using a variable contrast stimulus device (figure 6) that diffused the dot pattern visual image with incremental percentages of scattered gray light (Figure 7). This device consisted of a commercially available 12” x 12” privacy glass window manufactured by Polytronix. The design of this device allowed for variability of see-through visibility by electronically controlling the laminated polymer-dispersed liquid crystal film, sandwiched between the window’s two layers of glass. When increasing voltages were applied to the variable contrast stimulus device, the see through capability incrementally changed from an optically clear state to a cloudy gray translucent barrier.

To adjust the voltages applied to the window, a Variac manual potentiometer was connected between the power supply and the saturation window. This adjustable-contrast window was mounted within the VVSD directly in front of each subject. When participants were seated in the VVSD they were limited to viewing the interior surface of the visual surround through the variable contrast window. This was accomplished by blocking the subjects' peripheral fields of view by means of a cloth hood, which covered the subjects' heads and prevented viewing areas beyond the contrast window. To ensure uniformity of brightness and aid with qualifying the visual contrast characteristics of the visual stimulus, light sensors were mounted inside the window (under the hood) for sensing light levels between subject and the window. Light sensors were also placed outside the color saturation window for the purpose of sensing illumination of the area from the window to the interior wall of VVSD. Luminance inside the VVSD was held at a constant 21 cd/m$^2$ and kept between 7-8 cd/m$^2$ within the hood. Since the variable contrast window was mounted 7 inches from the subject's face, the field of view of the VVSD was limited to 80° of visual angle.

*Figure 6:* Variable contrast window with potentiometer in the lower left portion of the image.

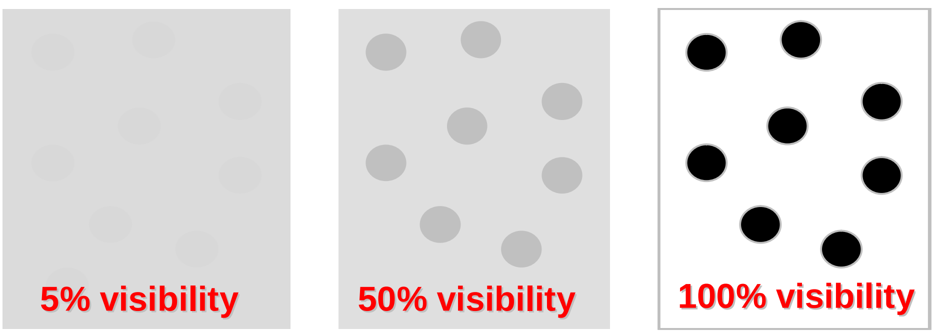


*Figure 7*: Appearance of VVSD surround dot pattern when viewed through the variable contrast stimulus device. The image on the left represents near maximum gray saturation and the image to the right indicates a condition of zero saturation.

*Procedures*

*Variables.* The independent variable for this experiment was the color saturation component of visual contrast. The dependent variables for establishing threshold values included the subject's report concerning the detection of sphere motion (button "on" = presence of sphere motion / "off" = absence of sphere motion) and the presence or absence of vection (button on or off). These two dependent variables were measured in separate sessions.

*Pilot Study.* A pilot study was performed on six subjects to finalize the protocol and establish an approximate (near threshold) color saturation contrast range for final testing. Each subject in the pilot study was tested using the method of adjustment described by Ehrenstein and Ehrenstein (1999); subjects experienced six separate trials with three contrast window voltage adjustments starting at 0% and adjusting up until surround motion or vection was experienced; followed by three adjustments starting at 100% and adjusting down. This procedure made it possible to establish an approximate voltage level for subjects' initial recognition of surround motion and induction of vection. These voltage values were used to establish the threshold range of 15-25V for dot pattern motion detection and 14-29V for onset of vection.

*Main Experiment.* For each subject, the first day was committed to filling out questionnaires and consent forms. The second day consisted of two main experiment sessions per subject. For session 1, each subjects' color saturation contrast thresholds for motion detection were determined and for session 2, individual color saturation thresholds for induction of vection were established. The contrast levels used in sessions 1 and 2 were executed in random order for all trials and session 1 always preceded session 2.

*Session 1 Description - Motion Detection Threshold*: The method of constant stimuli was used to establish final motion and vection thresholds. This method allowed experimenters to establish a probability curve representing the likelihood of subjects reporting perception of either surround or self-motion (vection) within a range of values that approximated the threshold values. For this portion of the experiment, researchers employed 11 different contrast levels (i.e., variations of percent contrast) within the contrast range established in the pilot study. Each of the chosen contrast levels was presented 4 times, for a total of 44 separate threshold judgments.

*Session 2 Description - Vection Threshold*: The method was the same as in Session 1. However, 16 contrast levels were randomly presented during 4 separate trials, for a total of 64 levels. For this session, subjects were asked to press an "on" button as soon as they felt the illusion of self motion at a given contrast level.

*Procedure for both trials (Session 1 or 2):* During each trial, the subject's eyes were open with the contrast screen initially translucent during the period required to start the

VVSD turning in a randomly-selected direction left or right. When the VVSD reached the desired velocity of 15 deg/s, the visual contrast screen was remotely switched to the pre-designated color saturation value for that particular trial; at this point, timing latency of subject recognition for either dome motion or onset of vection began. Once subjects detected what they perceived as either dot pattern motion or self motion, they were instructed to press a hand-held button to the "on" position and simultaneously respond verbally as to whether the perceived target motion was left or right. After subjects reported each target event, the VVSD was stopped and then restarted for the next randomly-designated direction and color saturation screen value.

*Determination of Thresholds*. For this experiment, color saturation threshold was defined as the color saturation (contrast window voltage setting) at which the direction of perceived dot motion or self motion was reported correctly during three out of four (75%) presentations. Based upon these observations, percent correct values were plotted across the range of color saturation seen through the contrast window. Since each participant had two types of psychometric functions to perform (the first was motion threshold judgments with 44 saturation contrast levels and the second, judging vection threshold over 64 color saturation levels) there were a combined total of 108 judgments for each subject. The mean and standard deviation of the grouped data determined an overall threshold level for motion and vection for this population. In addition, once all participants were tested, the contrast vs. threshold slopes for motion detection or self-motion detection were also evaluated and plotted.

*Approximate Duration of the Experiment*. All subjects were able to complete the 108 threshold judgments for Sessions 1 & 2 during the 90 minutes period they were inside the VVSD. Session 1 lasted for approximately 15 minutes and was followed by a five minute rest period prior to starting Session 2. The second session was conducted over a 45 minutes period that was broken up into four trials with a two minute break allowed between each trial..

*Contrast Determination*. A Sekonic L-758C light meter was used to record luminance while viewing the interior of the VVSD through the contrast window for each contrast setting of the protocol. Five individual areas within the window viewing area were measured for luminance (cd/m$^2$) and recorded for each setting (14-29V, and 40V, Table 1). The formula listed below this paragraph provides the basis of how color saturation visual contrast was determined using average luminance of the background (white areas of the interior of the sphere) minus luminance of the foreground targets (black dots) divided by the average luminance across all values of background and foreground, with the results of these measurements shown in Table 1. These values were then used to assess subject reported thresholds for motion and vection.

$$\frac{(\textbf{Luminance Background - Luminance Foreground})}{\textbf{Average Luminance across both}} \textbf{ = Color Saturation Visual Contrast}$$

*Table 1.* Conversion to Color Saturation Visual Contrast

| Window Voltage* | Contrast Calculations |
|---|---|
| 40 | 8.4 - 4.4 / 6.4 = 0.625 |
| 35 | 8.8 - 5.4 / 7.1 = 0.479 |
| 30 | 8.6 - 6.5 / 7.6 = 0.276 |
| 29 | 8.6 - 6.7 / 7.7 = 0.247 |
| 28 | 8.5 - 7.5 / 7.7 = 0.195 |
| 27 | 8.8 - 7.5 / 8.1 = 0.160 |
| 26 | 8.6 - 7.5 / 8.1 = 0.136 |
| 25 | 8.5 - 7.6 / 8.0 = 0.113 |
| 24 | 8.1 - 7.5 / 7.8 = 0.077 |
| 23, 22 | 8.6 - 8.0 / 8.3 = 0.072 |
| 21 | 8.2 - 8.0 / 8.1 = 0.025 |
| 20 | 7.6 - 7.5 / 7.6 = 0.0131 |
| 19 | 7.9 - 7.8 / 7.9 = 0.0127 |
| 18 | 8.0 - 7.9 / 8.0 = 0.0125 |
| 17 | 7.5 - 7.5 / 7.5 = 0.000 |

*Window voltages were used initially and later converted to calculated contrast values. The window value of 40 V is equivalent to total visibility (maximum contrast) and the window values of 17 V or less are equivalent to zero contrast or totally translucent window conditions.

## Results

*Pilot Study*

Approximate values for color saturation visual contrast thresholds were determined (for motion and vection) by making incremental voltage adjustments to a visual contrast window. These values were then used to estimate a vection threshold range, over which subjects would be tested during the main portion of the study. Three order-balanced thresholds in ascending order followed by three in descending order were recorded for reported motion and vection during this initial pilots study; from this data a mean value was determined by averaging the six threshold estimates. By employing window voltages from 0 to 100, a mean window voltage of 20.3 $\pm$ 3.3 (contrast value 0.013) was established for surround motion detection time and a mean window voltage of 21.7 $\pm$ 5.1 (contrast value 0.072) for vection. Based upon this data, the desired ranges for motion and vection threshold testing in the main experiment were set at 15-25V (contrast range 0.00 – 0.113) for motion threshold estimates and 14-29V (contrast range 0.00 – 0.247) for vection threshold estimates.

*Main Experiment*

*Dependent variable 1- (Sensation of sphere motion with no vection illusion).* Each of the twenty subjects completed 44 randomly selected session 1 trials that varied with respect to the amount of gray color (saturation) overlaid upon the moving white and black dot pattern. Although subjects were exposed to 11 different contrast levels (which had been previously determined to fall near the predicted threshold level), each contrast value was tested four times (4 x 11 setting), thereby providing individual subjects with a total of 44 trial events for determining color saturation thresholds for sphere motion (Appendix B). Results of these trials indicated motion of the dot pattern was detectible at very low contrast levels (figure 8): however, at the lowest contrast level (contrast = 0.00) only four

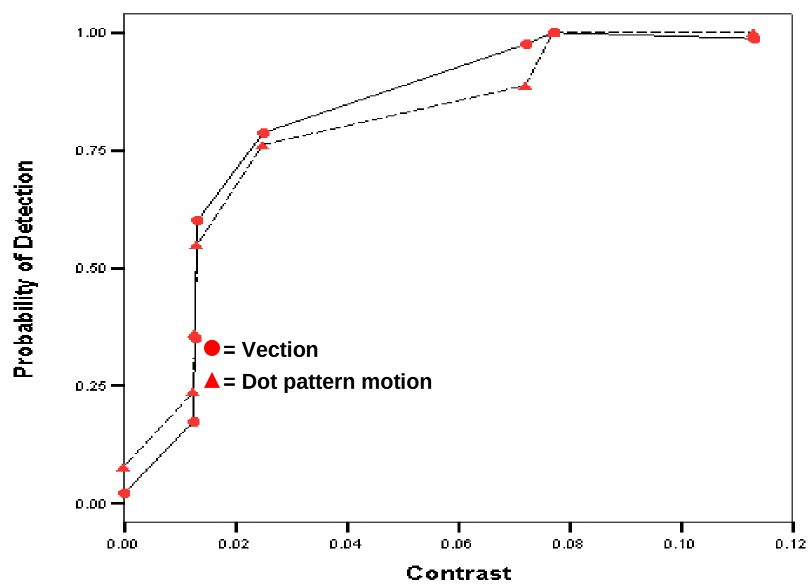


Figure 8: Subjects' reported times for detection of dot pattern motion and vection illusion.

out of 20 subjects reporting seeing moving patterns once out of four attempts (5% detection rate). When the contrast value reached half of the maximum session 1 test value (contrast = 0.013), 59% of the subjects reported seeing the moving dot pattern. After the color saturation visual contrast reached its maximum test value (contrast = 0.113), subjects reported seeing the moving dot pattern with 100% accuracy. Across the range of visual contrast values used for this portion of the study, the subjects' elapsed time for detecting and reporting onset of dot pattern motion ranged from 1.39 $\pm$ 0.63 sec at the highest contrast setting to 2.82 $\pm$ 1.67 sec for the lowest. An analysis of variance (ANOVA) of this data indicated the main effect of visual contrast color saturation did have a significant ($p < 0.01$) inverse impact upon reported dot motion response times.

*Dependent variable 2 – (Sensation of vection illusion).* All twenty subjects completed 52 session 2 trials, during which time they were asked to report sensations of self motion (vection) during exposure to moving dot patterns with varying color saturations (Appendix C). For this series of trials, the probability of detection (for vection) was

similar to session 1 (figure 8), with the exception of a significant increase in latency between presentation of the visual stimulus and reported vection sensations. Over the experimental range of visual threshold contrast levels presented during session 2, the vection detection rate was 5% at the lowest value (contrast = 0.0), 62% at the medium threshold range (contrast = 0.013), and 99% at the highest test level (contrast = 0.247). An ANOVA comparison of the data indicated that (similar to dot motion detection) visual contrast color saturation also had a significant ($p < 0.01$) inverse impact upon reported onset of vection.

*Dependent variable 3 – (Subjective assessment of vection strength).* During session 2, subjects were asked to verbally report the strength of any vection illusion they experienced using a rating scale of 1 to 5; with 1 being the weakest sensation and 5 the strongest. At the highest visual contrast level, subjects reported the strongest vection rating of 3.87 $\pm$ 0.79, which decreased to a rating of 2.95 $\pm$ 0.78 at the medium contrast range. With the lowest visual contrast value (maximum gray color saturation), vection strength became further attenuated reaching a subjective assessment rating of 2.13 $\pm$ 0.74 (figure 9). When reported strength of self perceived motion (vection illusion) was correlated with visual contrast color saturation, there appeared to be a significant positive relationship between these two factors ($r = 0.988$, $p < 0.05$).

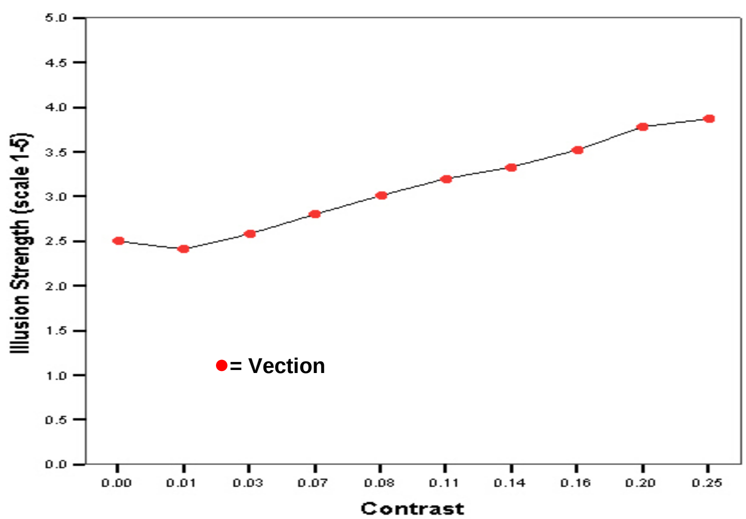


Figure 9: Subjects reported strength of vection illusion.

*Dependent variable 4 – (Latency between detection of sphere motion and onset of vection).* For this portion of the experiment, latency for reported sensations of vection ranged from 14.43 $\pm$ 8.83 seconds for the highest contrast level to 10.97 $\pm$ 2.28 seconds at the lowest contrast setting. In comparison, delays in recognizing motion of the dot pattern were significantly less with a latency of 3.24 $\pm$ 0.74 seconds for the lowest contrast, and 0.63 $\pm$ 1.39 seconds for the highest. A Student's T test assessment of paired samples indicated the difference between these two variables was highly significant ($p< 0.001$). Latency for detection of dot motion correlated significantly with

visual contrast color saturation (r = -0.912, $p > 0.03$, 2-tailed) and for vection illusion latency related to visual contrast color saturation also indicated a significant inverse relationship (r = .928, $p > 0.01$).

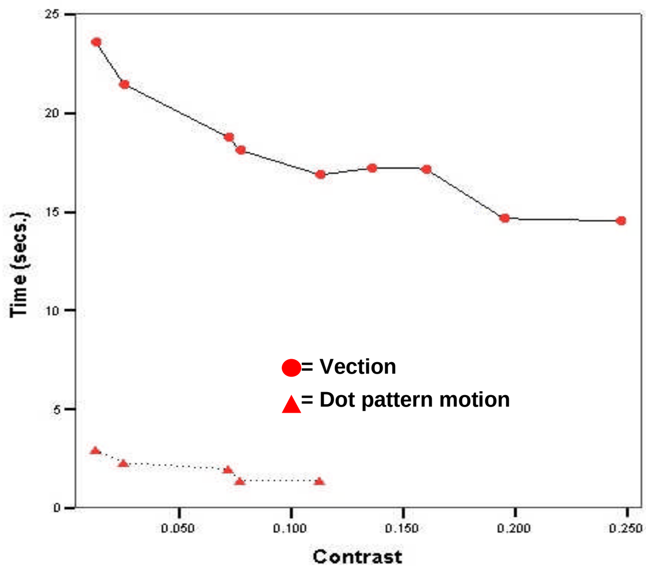


Figure 10: Latency for recognition of dot pattern motion and onset of vection illusion.

## Discussion

The results of this study indicate that visual contrast thresholds for detection of dot motion and onset of vection are nearly identical, with both events occurring within a relatively low visual contrast range. With a calculated visual contrast of only 0.113, approximately 60 percent of the subjects reported dot pattern motion with session 1 and sensations of vection during session 2. Since threshold levels for both events were so similar, it raises the question as to whether motion detection and vection should be considered as two different processes. Although both events (dot motion detection and vection) first appeared at a common visual threshold level, the findings of this study indicate that sensations of vection are significantly delayed ($\overline{X}$, 11.0 – 14.4 sec) in comparison to recognition of dot pattern motion ($\overline{X}$, 0.5 – 1.4 sec). Since, Previc, Liotti, Blakemore, Beer, and Fox (2002) reported that visual stimuli associated with vection (i.e., those with coherent, wide fields-of-view) tend to activate distinct areas of the brain (compared to incoherent visual dot pattern motion) the observed differences in detection latency lend support to the conclusion that, although these two events may have the same underlying sensory mechanisms, they are distinctly different perceptual processes.

The data curve illustrating observed threshold information for motion and vection (figure 8), portrays a steep rise in the probability of detection for both events; thereby suggesting the threshold visual contrast stimulus generated an all or none response. Since the steepness of the stimulus/response curve begins at a relatively low level of visual

contrast, it indicates that vection and target motion can be readily perceived when visual cues are minimally detectable.  To help illustrate how visual variations of the stimulus change relative to the amount of color saturation, figure 11 provides four different color saturation views of an outdoor reference viewed through the variable contrast window. In this example, a photo of a natural scene at the experimental visual contrast threshold level of 0.013 is shown in Figure 11c, along with comparison views of the same scene at other contrast values above and below threshold (Figure 11a and 11b are above threshold and figure 11d is below).  Figure 11c indicates that only small amounts of visual contrast are needed to perceive the presence of scenery detail in this example.

View 11a: contrast = 0.62 (no color saturation).

View 11b: contrast = 0.25 (≈ 25% color saturation).

View 11c: contrast = 0.01 (≈ 75% color saturation).

View 11d: contrast 0.0 (≈ 100% color saturation).

Figure 11: Views seen thorough the variable contrast window with variation in color saturation ranging from the highest calculated contrast level (0.625) to the lowest (0.0).

Since latency for dot motion detection and recognition of vection revealed a negative correlation with contrast level, it implies that increasing visual contrast by decreasing color saturation also decreases the time needed for detection.  These findings are not in agreement with the data shown in Sauvan and Bonnet (1993) who found that once a visual contrast threshold level was reached, latency of curvilinear vection did not vary significantly with further contrast improvements. However, this inconsistency might be explained by the fact that Sauvan and Bonnet used visual contrast levels that varied between 35% to 56 % and 20% to 41%, as opposed to this study where contrast values were at or near a predetermined threshold range which involved a significantly lower percent contrast (0% to 25%).  This narrower range of stimulus presentation most likely increased the protocol sensitivity, and thereby allowed for a more qualitative assessment of the relationship between visual contrast resolution and latency of target motion detection.

In addition to latency of recognition, vection illusion strength was also positively correlated with contrast level.  This correlation implies that an increase in contrast produces a corresponding increase in perception of realism for the vection illusion.   If the inverse is also true (i.e., decreased contrast equates to reduced illusion strength), this finding may have some relevance toward better understanding how vection can impede pilot performance during helicopter brownout conditions.  Since brownout events usually begin with high visual contrast and then rapidly degrade to low visibility conditions, the data suggests that risk of vection induced disorientation may be greatest during the beginning phases of hover transition.  Unfortunately, initial transition to hover is also

considered a high mental workload event which may further add to the risk of vection induced disorientation during this critical phase of flight.

This experiment has helped to identify and define the impact that color saturation has upon detection of target pattern motion and onset of vection illusion. Since both of these factors have the potential to impact spatial perception when visual conditions become degraded, the results of this study will help create specifications for future research and design solutions aimed at increasing vehicle operator (air, land, or sea) performance in extreme environments. Understanding when vection illusions are likely to occur is of practical value for individuals who are especially vulnerable to degraded visual spatial cues, such as helicopter pilots, astronauts returning from space, or persons suffering from visual-vestibular vertigo (Young, Mendoza, Groleau, & Wojeik, 1996). By identifying color saturation visual contrast thresholds, for both target motion and onset of vection, this study has helped establish an important minimum standard criterion for onset of both events.

## Acknowledgements

We would like to thank Dr. Ben Lawson for his technical and professional contributions to the work and Ms. Shauna Legan for assistance in completing the study.

## Disclaimer

The views expressed in this article are those of the author and do not necessarily reflect the official policy or position of the Department of the Navy, Department of Defense, nor the U.S. Government.

## Sources of Support

This project was funded by work unit number 70802.

## Copyright statement



## Distribution Statement

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**Appendix A**

**CONSENT DOCUMENT**

The Effect of Contrast on the Visually-Induced Illusion of Self-Motion, NAMRL.2008.0003, LCDR York, PI

## VOLUNTARY CONSENT TO PARTICIPATE IN A RESEARCH STUDY

You are being asked to volunteer to participate in a research study titled "The Effect of Contrast on the Visually-Induced Illusion of Self-Motion". This study is being conducted by researchers at the Naval Aerospace Medical Research Laboratory (NAMRL), Pensacola, FL and at the US Army Aeromedical Research Laboratory (USAARL). About 20 people will take part in this study at NAMRL on board NAS Pensacola from May 2008 to May 2009. Your participation is completion voluntary. If there is anything in this Consent Document that you do not understand, be sure to ask the investigators to explain that portion of the study. If you have any questions, do not hesitate to ask them.

### Why is this study being done?

In the area of spatial disorientation, the illusion of self-motion (vection) may play an important role. For instance, a pilot may be in a situation where he/she makes a wrong decision based on this illusion. Therefore the more we know about this illusion and how to identify its characteristics makes for a safer work environment.

The purpose of this study is to determine the contrast threshold for vection. This work will further the understanding of when vection occurs and its relationship to contrast. Discovering when someone is most susceptible to the effects of vection could advance the development of potential simulator applications in the field of spatial disorientation training.

We are asking you to take part in this study because you are in the aviation pipeline and this spatial disorientation phenomenon potentially will affect you at some point in your career.

### What will happen if you decide to take part in this study?

You will be asked to spend about 3 hours over 2 days in this study. The first study day will take approximately ½ hour and the second day approximately 2 ½ hours.

- The schedule for the first day consists of filling out paperwork (i.e. motion sickness susceptibility questionnaire, "MSSQ", medical questionnaires (each visit) and consent forms).
- The second day will consist of 2 testing sessions in the Visual Vestibular Sphere Device (VVSD). This device is a 12 ft. by 12 ft. hollow sphere into which you will be seated. The device will rotate around you and you will be asked to make judgments based on how you feel. The one session will determine your motion threshold and another session will test your vection (illusion of self-motion) threshold. During the threshold measurements we will be asking whether you see motion or if you feel you are moving and the direction of that movement. The specific questions you will be asked are for instance: for motion effect- (Is the sphere moving about you?), and vection effect- (Does it feel as though you are moving and the sphere is stationary?). Each session should take approx. 30 min. to complete. There will be approximately 25 judgments for

session 1 and session 2, giving 50 threshold adjustments in total. You will be given rest breaks between sessions for roughly 10-15 minutes and 30 sec. to 2 min. between individual judgments.

- You cannot take part in this study if you are highly susceptible to motion sickness, as determined by the Motion Sickness Susceptibility Questionnaire "MSSQ". If you are pregnant you will be excluded from this study. The researchers have no evidence that participation in this study has harmful effects on a developing fetus but as a precaution we will exclude pregnant females.

**What are the risks if you take part in this study?**

The investigators believe that the risks or discomforts to you are negligible. Your participation is voluntary and you may stop participating at any time, for any reason.

You must confirm that, to the best of your knowledge, you are not now pregnant, and that you do not intend to become pregnant during the study. If you are female, you will be asked to take a urine pregnancy test before each study visit to confirm that you are not pregnant. If you become pregnant, your participation in the study will be stopped because the possible risks to the developing fetus from the study drug are not known. If you suspect that you have become pregnant during the study, you must notify the principal investigator, LCDR Yancy York immediately.

**What happens if you are injured because you took part this study?**

If you are injured or become ill during participation emergency medical personnel will be called immediately. Medical care will be available to you through your Navy health care provider. You can get further information about this from **LT Debra Banks at 850-452-2458**. By signing this consent form, you will not be giving up any legal rights.

**Are there benefits to taking part in this study?**

You are not expected to receive any direct benefit from taking part in this study.

**What health information will be collected and will it be kept confidential?**

If you choose to be in this study, the study staff will obtain the following information about you, including information that will identify you. "You will be asked to fill out a questionnaire asking about your general health and susceptibility to motion. Questions about your health will be asked to determine if you have a history of respiratory, heart, metabolic conditions. Your answers will be used to determine if you qualify for this study. This information will be used only by study personnel and will be maintained for a period of five years.

You may change your mind and revoke (take back) your permission to collect or use your health information at any time. To revoke your permission, you must write to the person in charge of the study, LCDR Yancy York at yancy.york@med.navy.mil. When you revoke your permission, no new health information about you will be gathered after that date and you may no longer be allowed to participate in the study. Information that has already been gathered may still be used and there is no guarantee that it will be removed from the electronic database for this study. You also have the right to review and copy your health information for as long as hard copies of the Motion Sickness Questionnaire, Recruitment Day Medical Form, and Participation Day Medical Form are maintained by contacting the person in charge of the study, LCDR Yancy York, at yancy.york@med.navy.mil.

LCDR Yancy York is responsible for storing your health information and other information collected about you during the study. This information will be protected by storage of all paper copies of your information in a locked filing cabinet in room 7A at Naval Aerospace Medical Research Laboratory. Electronic data will be stored on a password protected computer. Access to all data will be limited to staff involved in this study. The health information you disclose will not be used by or disclosed (released) to another institution.

The results of this study may be published in DoD technical reports, scientific journals, or presented at scientific meetings. No publication or presentation about the research study described above will reveal your identity without another authorization from you. Lastly, individuals from official government agencies, such as the Department of Defense and the U.S. Navy, may inspect your research records to ensure that the rights and safety of all research participants are protected.

By signing this consent form, you are giving permission to use [and disclose] the health information listed above for the purposes described in this form. If you refuse to give permission, you will not be able to be in this study.

**What are your rights if you take part in this study?**

Taking part in this study is your choice. Your participation must be completely voluntary. If you decide to take part, you may still leave the study at any time. No matter what decision you make, there will be no penalty to you and you will not lose any benefit to which you are otherwise entitled.

If you do choose to leave the study, tell the study staff as soon as you can so they can ensure an orderly withdrawal.

Your participation in this study may be stopped at any time by LCDR Yancy York, the person in charge of the study, without your consent because we find out it is not safe for you to stay in the study, if you cannot achieve the vection illusion, if you have extremely long time exposure to appreciate vection, or if you are not coming for your study visits when scheduled.

Major new findings that develop during the course of the research that may relate to your willingness to continue participation will be provided to you.

**What if you have questions about the study?**

Do not sign this consent form unless you have had a chance to ask questions and have received satisfactory answers to all of your questions. You should contact the following individuals to answer your questions:

**For questions about the research**, contact LCDR York at (850) 452-4302 or yancy.york@med.navy.mil.

**For questions about your health or safety in this study, or if you feel that you may have been injured**, contact **LT Debra Banks at 850-452-5242 Ext 127** or debra.banks@med.navy.mil.

**For questions about the ethical aspects of this study or subjects' rights**, contact **Ben Lawson at 850-452-2504** or ben.lawson@med.navy.mil. He is the Chairman of the Naval Aerospace Medical Research Laboratory Institutional Review Board, a group of people who review the research to protect your rights.

**CONSENT TO TAKE PART IN THIS RESEARCH STUDY**

You have read the information in this consent form. You been given an opportunity to ask questions about this study and its procedures and risks, as well as any of the other information contained in this consent form. All of your questions have been answered to your satisfaction. You understand that this is research. By signing below, you freely give your consent to be in this research study as it has been explained to you. You authorize the use and disclosure of your health information to the persons listed in the health information and privacy section of this consent for the purposes described above. You have been given a copy of this form for your personal records and a statement informing you about the provisions of the Privacy Act.

| ___________________________ | ______________________________ | ______________ |
|---|---|---|
| Signature of research participant | Printed name of research participant | Date |

| _________________________ | _________________________ | ______________ |
|---|---|---|
| Signature of Person<br>Conducting Consent Discussion | Printed Name of Person<br>Conducting Consent Discussion | Date |

| _________________________ | _________________________ | ______________ |
|---|---|---|
| Signature of Witness | Printed Name of Witness | Date |

**Appendix B**

**TIME TO MOTION STATISTICS**

Subjects' data for detecting dot pattern motion in relationship to color saturation visual contrast.

| Subject | 25 | 24 | 23 | 22 | 21 | 20 | 19 | 18 | 17 | 16 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.8 | 1.5 | 0.91 | 0.91 | 1.2 | 5.91 | | | | | |
| | 1.11 | 1 | 2 | 3.2 | 14.5 | 1.09 | | 3.7 | | | |
| | 0.69 | 1.5 | 0.78 | 1.59 | 6.7 | | | | | | |
| | 0.7 | 0.8 | 1 | 0.91 | 5.2 | | 1 | | | | |
| 2 | 1.2 | 0.8 | 1.1 | 1.5 | 1.22 | 1.11 | | | | | |
| | 0.9 | 0.91 | 1.8 | 1 | 1.31 | 5.4 | | | | | 10 |
| | 1.09 | 1.2 | 1.9 | 1.5 | | 1.09 | 7.9 | 5.8 | | | |
| | 0.8 | 1.09 | 1.02 | 1.2 | 1.3 | 1 | | | 9.4 | | |
| 3 | 1.61 | 1.41 | 1.22 | 5.3 | 1.09 | | 1.2 | 4.41 | | | |
| | 1.09 | 1.09 | 2.3 | 1 | | 1.31 | | | 1 | | |
| | 1.39 | 1 | 2 | 1.59 | 2.8 | 1.09 | | | | | |
| | 0.91 | 1 | 0.81 | 1.2 | 0.81 | | 1.3 | | | 1.41 | |
| 4 | 1.41 | 1.2 | 3.11 | 4.59 | 1.91 | | | | | | |
| | 1 | 1.89 | 1 | 2.5 | | | | | | 2.5 | 4.2 |
| | 1.3 | | | | | | | | | | |
| no data | | | | | | | | | | | |
| 5 | 2.7 | 1 | 2.7 | | 1.5 | 1.2 | 1.11 | | 1.59 | | 2.8 |
| | 1.5 | 1.3 | 1.6 | 1.5 | 1.11 | 6.9 | 5.11 | 3 | | | |
| | 1 | 1.2 | 1.8 | 1.09 | 1.81 | | | 2.5 | | | |
| | 1.18 | 0.91 | 1 | 1.5 | 1.41 | 1.3 | 1.7 | | | | |
| 6 no data | | | | | | | | | | | |
| 7 | 1 | 0.91 | 1.19 | 2.22 | | | | 1 | | | |
| | 1.3 | 0.91 | 1.31 | 1 | 1.5 | | | | | | |
| | 1 | 1.2 | 1.41 | 1 | 2.1 | | 2.91 | | 1 | | |
| | 0.89 | 0.98 | 1.11 | 2.5 | 3.3 | 1.2 | 2.11 | | | | |
| 8 | 1.3 | 1 | 1.31 | 1.3 | | 1.7 | 1.3 | 2 | | | |
| | 1.92 | 2.5 | 1.6 | | 1.9 | 2.31 | 2.8 | | | | |
| | 1.3 | 1.5 | 3.4 | 4.09 | 3.2 | 4 | | | | | |
| | 1.41 | 1.7 | 1.91 | 2.3 | | | | | | | |
| 9 | 1.2 | 1.7 | 2.6 | | | | | | | | |
| | 1.61 | 2 | 1.6 | | | 5.11 | 5.2 | | | | |
| | 2.09 | 2.5 | 3.9 | 2 | 7.8 | | | | | | |
| | 2.11 | 1.81 | 1.8 | 2.6 | 3.2 | 3.5 | | | | | |
| 10 | 0.81 | 1.41 | 1 | 1.8 | 1.5 | 2.6 | 1.39 | | | | |
| | 0.91 | 0.8 | 1.2 | 2 | 1.19 | | 8.7 | | | | |
| | 0.8 | 0.9 | 1 | 1.39 | 0.91 | 12.2 | | | | | |
| | 1 | 1.11 | 1.2 | 1.39 | 1 | 7.31 | 2.2 | 1.2 | | | |
| 11 | 1.7 | 1.2 | 1.09 | 3.7 | | 8.6 | 3.4 | 2.7 | | | |
| | 1.7 | 1.89 | 3 | 1.5 | | | | | | | |
| | 1.5 | 2 | 1.6 | 7.9 | | 3 | | | | | 4.11 |
| | 1.59 | 1.89 | 2.39 | 10.7 | 1.89 | | | | | | |

| Subject | 25 | 24 | 23 | 22 | 21 | 20 | 19 | 18 | 17 | 16 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 | 1.61 | 1.02 | 1.11 | 1.09 | 4.63 | | | 2.3 | | | |
| | 1.2 | 1.7 | 3.8 | 1.2 | 1.5 | | | | | | |
| | 1.61 | 1.3 | 1.3 | 1.2 | | | | | | | |
| | 1.3 | 1.42 | 1.19 | 2.2 | 1.19 | | | | | | |
| 13 | 1.7 | 1.3 | 1.52 | 1.91 | 1.81 | 2.48 | 1.3 | 1.41 | 1.7 | | |
| | 1.3 | 1.61 | 1.3 | 3.11 | 1.59 | 1.39 | | | | 2.69 | |
| | 1.11 | 1.09 | 1.41 | 1.61 | 1.2 | 3 | | | | | |
| | 1 | 1.61 | 1.6 | 1.19 | 1.2 | 1.5 | | | | | |
| 14 | 1.19 | 1.31 | 2.8 | 2.5 | | 3.19 | | | | | |
| | 1.7 | 2 | 1.8 | | 2.3 | | | | | | |
| | 1.39 | 1.7 | 3.9 | 1.89 | 1.41 | | | | | | |
| | 1.22 | 1.41 | 3.3 | 2 | 1.89 | | | | | | |
| 15 | 4 | 2.59 | 2 | 4.11 | 2.59 | 3.61 | 3.2 | 6 | 2.5 | | |
| | 3.89 | 1.59 | 2.41 | 2.38 | 2.09 | | | | | | |
| | 3.3 | 2.11 | 1.61 | 2.3 | 2.5 | 7.2 | | | | | |
| | 2.3 | 1.8 | 1.61 | 2.39 | 2.09 | 1.8 | | | | | |
| 16 | 1.02 | 0.91 | 2.08 | 2.19 | 1.09 | 1.19 | 1.3 | | | | |
| | 0.91 | 1.09 | 1.2 | 1.09 | 3.4 | 5.92 | | | | | |
| | 1 | 1.19 | 1.2 | 1 | | 1 | | | | | |
| | 1 | 1.59 | 1.09 | 1.41 | 2.7 | 2.91 | | | | | |
| 17 | 1.3 | 2.3 | 2.11 | | 1 | 1.09 | | | | | |
| | 2 | 1.59 | 2.81 | 2.09 | | 4.31 | | 3.61 | | | |
| | 1.3 | 1.39 | 1.8 | | | | 3.11 | | | | |
| | 2.2 | 1.39 | 3.3 | 1.28 | | | | | | | |
| 18 | 0.89 | 1.11 | 0.91 | 1.11 | 1 | 0.91 | | 1.11 | | | |
| | 1 | 1 | 0.91 | 0.89 | 2 | | | 1.09 | | | |
| | 1 | 1 | 1.09 | 1.41 | 3 | | | | | | |
| | 0.81 | 1.09 | 1 | 1 | | 0.8 | 1.09 | 1.09 | | | |
| 19 | 2 | 1.5 | 1.41 | 1.39 | 1.39 | 1.59 | | | | | |
| | 1.7 | 1.5 | 3.19 | 2.61 | 2.1 | 1.5 | | | | | |
| | 1.41 | 1.5 | 1.2 | 3.11 | 1.3 | 1.39 | | | | | |
| | 1.3 | 1.09 | 1.59 | 1.31 | 1.09 | | 1.7 | | | | |
| 20 | 1.22 | 1.31 | 1.7 | 1.2 | 1.19 | 1.59 | 3.7 | 5 | | | |
| | 1.3 | 1 | 1.09 | 2.2 | 1.19 | | | | | | |
| | 1 | 1.31 | 3.48 | 3.39 | 1 | | | | | | |
| | 0.8 | 1.5 | 0.89 | 1.11 | 5.41 | 4.2 | | | | | |
| SD | 0.632704 | 0.423097 | 0.830033 | 1.602 | 2.187 | 2.525 | 2.123 | 1.688 | 3.249 | 0.691 | 3.213 |
| AVG | 1.393333 | 1.386892 | 1.761892 | 2.124 | 2.325 | 3.058 | 2.814 | 2.819 | 2.865 | 2.2 | 5.278 |

# Appendix C

## TIME TO VECTION STATISTICS (IN SECONDS)

Subjects data indicating time for onset of vection relative to variation in color saturation visual contrast.

**High voltage = high contrast and clear window

| Contrast | 0.625 | 0.247 | 0.195 | 0.16 | 0.136 | 0.113 | 0.077 | 0.072 | 0.072 | 0.025 | 0.0131 | 0.0127 | 0.0125 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Subject# | 40v =demo | 29 | 28 | 27 | 26 | 25 | 24 | 23 | 22 | 21 | 20 | 19 | 18 | 17 |
| 1 | | 9.7 | 17.1 | 15.1 | 37 | 6.2 | 15.2 | 10.9 | 11.3 | 30 | 5.7 | | | |
| | | 5.5 | 4.4 | 10.2 | 10.1 | 4.7 | 14.7 | 5.1 | 11.8 | 8.1 | 11.9 | 5.4 | | 12.6 |
| | | 4.1 | 6 | 24.4 | 5.6 | 7.2 | 10.1 | 9.3 | 13.1 | 5 | 26.3 | 8.4 | 5.4 | |
| | | 5.3 | 5.3 | 5.4 | 10.7 | 8.7 | 9.9 | 8.9 | 6.5 | 4.1 | 6.7 | 5.2 | 9.3 | |
| 2 | | 19.8 | 17 | 20.4 | 20.8 | 25 | 44.1 | 16.8 | 32.9 | 33.7 | | | | |
| | | 15.2 | 20.4 | 24.7 | 18.9 | 13.9 | 19 | 16.7 | 29.5 | | 34.5 | | | |
| | | 18.8 | 13.4 | 32.5 | 17.4 | 20 | 15 | 36.8 | 45.9 | 28 | | | | |
| | | 9.8 | 16.2 | 14.9 | 26.2 | 15.4 | 20 | 22 | 38.3 | | | | | |
| 3 | | 8.9 | 5.3 | 9.5 | 8 | 12.5 | 19.7 | 10.4 | 10.1 | | | | | |
| | | 12.8 | 8.7 | 8.1 | 6 | 11.8 | 14.3 | | 13.5 | 24.9 | | | | |
| | | 7.9 | 8.1 | 17.3 | 10.9 | 11.4 | 10.2 | 11.4 | 14.6 | | | | | |
| 4 | | 3 | 5.8 | 7 | 6 | 6 | 6.6 | 14.2 | 8.7 | 12.3 | | | | |
| | | 5.9 | 6.2 | 5 | 7.1 | 4.9 | 10.6 | 4.7 | 5.9 | 24.6 | | | | |
| | | 5.4 | 5.8 | 6.7 | 8 | 4.3 | 4.9 | 7.8 | 8.2 | 9.1 | 9.2 | 11.4 | | |
| | | 5.6 | 3.5 | 5.6 | 5.9 | 6.7 | 7.7 | 9 | 11 | 10.1 | | | | |
| 5 | | 7.7 | 4.1 | 7.8 | 3.7 | 16.1 | 6.8 | 8.7 | 8.7 | 7.3 | 10.7 | 9.7 | | |
| | | 5.3 | 5.9 | 7 | 7.1 | 6.7 | 7.5 | 8.9 | 6.2 | 5.9 | 9.6 | 7.4 | 9.1 | |
| | | 6.1 | 6.5 | 6 | 6.9 | 6.1 | 6.7 | 9.4 | 7.8 | 7.3 | | 7.6 | | |
| | | 5.1 | 5.8 | 8 | 9.7 | 6.2 | 9.1 | 11.7 | 8.1 | 10.1 | 8.6 | | | |
| 6 | | 20 | 17 | 30 | 22 | 25 | 25 | 14 | | 40 | | | | |
| | | 13 | 10 | 18 | 16 | 11 | 9 | 10 | 14 | 16 | 26 | | | |
| | | 11 | 11 | 7 | 11 | 13 | 15 | 18 | 22 | | 18 | | | |
| | | 9 | 9 | 9 | 7 | 9 | 10 | 11 | | | 15 | | | |

| Contrast | 0.625 | 0.247 | 0.195 | 0.16 | 0.136 | 0.113 | 0.077 | 0.072 | 0.072 | 0.025 | 0.0131 | 0.0127 | 0.0125 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Subject# | 40v =demo | 29 | 28 | 27 | 26 | 25 | 24 | 23 | 22 | 21 | 20 | 19 | 18 | 17 |
| 7 | | 2.3 | 14.7 | 8.7 | 6.2 | 11.4 | 4.6 | 10.5 | 14.3 | 8.6 | 8.9 | | 6.6 | |
| | | 11.4 | 8.8 | 6.7 | 10.6 | 7 | 6.2 | 11.3 | 7.5 | 11.1 | 8.5 | 8 | | |
| | | 5 | 4.9 | 5.4 | 5.2 | 7 | 6.7 | 11.9 | 9.3 | 10.9 | 11.8 | | 6.3 | |
| | | 3.2 | 4.3 | 4 | 5.5 | 5.3 | 5.2 | 11.7 | 5.6 | 5.1 | 4.6 | 8.3 | 9.3 | |
| 8 | | 9.6 | 11.9 | 5.1 | 18.6 | 13.7 | 9.5 | 21.6 | 7 | | 23.5 | | | |
| | | 8.9 | 7.8 | 6.1 | 9.3 | 15.8 | 21.5 | 13.6 | 11.8 | 13.2 | 37.3 | | | |
| | | 7.6 | 10.5 | 11.4 | 11.3 | 8.6 | 15.6 | 15.5 | 16.4 | 11 | | 7.9 | | |
| | | 13.5 | 18.9 | 15.9 | 19.8 | 18.5 | 9.2 | 16.6 | 18.7 | 16.2 | 19.8 | | | |
| 9 | | 14.8 | 13.9 | 20.6 | 12.5 | 10.4 | 23.8 | 15 | 20 | 12.3 | 41.3 | | | |
| | | 13.1 | 12.3 | 23.4 | 15.3 | 28.3 | 36.7 | | 21.3 | 33.9 | | | | |
| | | 23.5 | 19.9 | 32.6 | 29.1 | 11.7 | 41.3 | 22.9 | 42.3 | 46.5 | 33.8 | | | |
| | | 25.5 | 29.5 | 18.4 | 33.4 | 27.8 | 21.2 | 27.9 | 42.4 | 35.3 | 32.5 | | | |
| 10 | | | 50.1 | 21.6 | 13.5 | 44.7 | 12.6 | 25.4 | | | | | | |
| | | 20.8 | 21.4 | 28.7 | 42.2 | 25.7 | 44.5 | 36.2 | 35.1 | 31.3 | | | | |
| | | 22.6 | 12.6 | 25.6 | 27.1 | 29.5 | 29 | 26.5 | 19.7 | 46.4 | 41.4 | | | |
| | | 40.4 | 16.4 | 33.5 | 35.6 | 21.5 | 34.5 | 52.2 | 29.6 | | | | | |
| 11 | | 8.2 | 11 | 19.7 | 10.6 | 8.7 | 6.9 | 13.6 | 15.8 | 27.5 | | | | |
| | | 12.5 | 12.3 | 7.7 | 12.5 | 12.8 | 6.9 | 9.1 | 12.8 | 14.1 | 25.4 | | | |
| | | 13.2 | 6.9 | 9.7 | 13.5 | 9.8 | 8.6 | 14.2 | 16.8 | 17.8 | | 13 | | |
| | | 8.8 | 9.9 | 11.6 | 12.6 | 11 | 9.4 | 13.7 | 14.9 | 15.8 | | 12.7 | 13.3 | |
| 12 | | 8.2 | 6.8 | 6.4 | 17 | 52.4 | 19.8 | 38 | 11.1 | | 43.4 | | | |
| | | 10.2 | 13.5 | 8.2 | 12.5 | 11.9 | 13 | 10 | 9.8 | 14.2 | 32.2 | 15.5 | 8.4 | |
| | | 8.1 | 11.7 | 7.9 | 17.5 | 14.1 | 14.4 | 11.5 | 15 | | | | | |
| | | 8.6 | 15.6 | 9.9 | 9.3 | 15.4 | 13.7 | 10.9 | 13.5 | 11.7 | 10.3 | | | |
| 13 | | 34.3 | 53 | 52.2 | 31.2 | 13.9 | 30.7 | 30.7 | 34.7 | 39.5 | | | | |
| | | 26.9 | 30.6 | 29 | 19.9 | 31.6 | 30.5 | 22.7 | 35.4 | 26.5 | 22.4 | | | |
| | | 35.9 | 31 | 31.5 | 32.2 | 31.1 | 24.1 | 20.6 | 29.1 | 20.3 | 32.6 | | | |
| | | 29 | 27.7 | 32.9 | 35.2 | 26.9 | 17.6 | 29.5 | 22.7 | 22.1 | 33.9 | | | |

| Contrast | 0.625 | 0.247 | 0.195 | 0.16 | 0.136 | 0.113 | 0.077 | 0.072 | 0.072 | 0.025 | 0.0131 | 0.0127 | 0.0125 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Subject | 40v =demo | 29 | 28 | 27 | 26 | 25 | 24 | 23 | 22 | 21 | 20 | 19 | 18 | 17 |
| 14 | | 26.7 | 21.3 | 17.7 | 33.8 | 30.2 | 36.9 | 31.2 | 29.2 | 53.3 | | | | |
| | | 15.9 | 21.2 | 26.3 | 20.6 | 19.4 | 20.9 | 17.5 | 15.8 | | | | | |
| | | 18.5 | 22.5 | 23.7 | 22.3 | 30.7 | 29.5 | 25 | 19.7 | 23.1 | 50.9 | | | |
| | | 21.9 | 21.8 | 21.2 | 17.1 | 25 | 25.1 | 30.2 | 30.7 | 27.3 | | | | |
| 15 | | 30.3 | 27.4 | 44 | 36.7 | 45.1 | 29.9 | 34.6 | 26.5 | 43.3 | 32.3 | 26.4 | 26.2 | |
| | | 22.8 | 16.5 | 29.7 | 30.9 | 29.5 | 22.3 | 30.6 | 33.5 | 21.1 | 36.4 | 33.4 | | |
| | | 30.1 | 19.9 | 30.2 | 28.8 | 26.7 | 28.2 | 29.4 | 25.1 | 22.4 | 34.7 | 17.9 | 23.7 | |
| | | 25.8 | 18.5 | 34.4 | 31 | 37.7 | 21.1 | 26.2 | 20.7 | 28.7 | 38 | 32.6 | 24.9 | |
| 16 | | 8.9 | 6.6 | 7.5 | 10.3 | 5.8 | 9.7 | 8.2 | 10.1 | 16.9 | | 12 | | |
| | | 5.9 | 6.4 | 9.2 | 8 | 7 | 7.9 | 7.2 | 9.1 | 8.8 | 10 | 12.8 | 10.7 | 13.2 |
| | | 7.3 | 8 | 8 | 8.6 | 5.9 | 7.7 | 6.1 | 10.6 | 7.6 | 8.2 | 9.4 | | 8.5 |
| | | 6.7 | 8.3 | 7 | 6.8 | 6.9 | 7.3 | 8.3 | 6.4 | 7.4 | 8.9 | 10.5 | 9.8 | 9.6 |
| 17 | | 8.9 | 22.1 | 19.3 | 23.2 | 19.2 | 27 | 24.9 | 18.7 | 22.4 | 24.6 | | | |
| | | 22.4 | 28.3 | 24.9 | 22 | 7.2 | 13.8 | 35.5 | 27.6 | 22.9 | 32.4 | | | |
| | | 21.1 | 14 | 22.9 | 21.2 | 21.9 | 28.5 | 19.5 | 26.8 | 16.2 | 23.5 | 27.1 | | |
| | | 23.6 | 18.4 | 20.4 | 23.1 | 23.1 | 29.2 | 30.1 | 23.2 | 28.2 | 42.4 | | | |
| 18 | | 6.5 | 7.3 | 6.2 | 14 | 6.5 | 9.8 | 8.1 | 4.7 | 5.6 | 6.2 | 39.4 | | |
| | | 6 | 7 | 5.9 | 5.7 | 8 | 8.9 | 10.7 | 10.6 | 11.8 | 12.9 | 12.1 | 10.4 | |
| | | 9.4 | 13.1 | 10.2 | 11.8 | 11.7 | 20.6 | 12.9 | 9.4 | 7.9 | 16.8 | 16.8 | 9.8 | |
| | | 14.4 | 15.5 | 10.5 | 11.2 | 12.5 | 11.1 | 15.1 | 7.1 | 14.1 | 18.9 | | | |
| 19 | | 25.7 | 28.2 | 23.1 | 26.8 | 20.2 | 44.5 | 35.1 | 42 | 31.3 | | 36.2 | | |
| | | 19.8 | 16.6 | 20.7 | 28.7 | 26.6 | 24.1 | 28.4 | 32.8 | 22.2 | 38.2 | | | |
| | | 21.9 | 20.2 | 20.4 | 26.9 | 19.9 | 27.2 | 20.1 | 31.3 | 30 | 18.8 | | | |
| | | 17.8 | 20.5 | 24.2 | 26.7 | 24.9 | 21.4 | 28.2 | 21.3 | 20.7 | 20.9 | | | |
| 20 | | 24.1 | 17.8 | 41.5 | 19.7 | 21.3 | 20.1 | 30.6 | | | | | | |
| | | 18 | 10.8 | 19.1 | 25.1 | 16.9 | 36.1 | 14.9 | | | | | | |
| | | 5.1 | 11.2 | 21.7 | 11.8 | 26.1 | 23.6 | 28.2 | 25.3 | | | | | |
| | | 18.8 | 15.9 | 19.1 | 15 | 23.6 | 14.1 | 26.8 | 10.8 | 28.3 | | | | |
| | SD | 8.830859 | 9.304669 | 10.64762 | 9.714596 | 10.43723 | 10.53331 | 9.989004 | 10.75051 | 11.77646 | 12.63104 | 10.16449 | 6.871459 | 2.280899 |
| | AVG | 14.42692 | 14.7557 | 17.25316 | 17.32911 | 16.93418 | 18.16835 | 18.73506 | 18.77973 | 20.14531 | 22.87347 | 15.65769 | 12.21333 | 10.975 |